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# Fourier Eisenstein transform on the space of rational binary quadratic forms

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## § 0. Introduction

Put  $G = GL(2, \mathbb{Q})$  and  $\Gamma = GL(2, \mathbb{Z})$ . Let  $X$  be the set of nondegenerate rational symmetric matrices of size 2:  $X = \{x \in M(2, \mathbb{Q}); {}^t x = x, \det x \neq 0\}$ . The group  $G$  acts on  $X$  via  $x \longmapsto gx {}^t g$  ( $x \in X, g \in G$ ). We put

$$X_K = \{x \in X; (-\det x)^{1/2} \in K \setminus \mathbb{Q}\}$$

for a quadratic field  $K$  and

$$X_{\mathbb{Q}} = \{x \in X; (-\det x)^{1/2} \in \mathbb{Q}^{\times}\}.$$

Then  $X$  is decomposed into  $G$ -stable subsets as follows:

$$X = \left( \bigcup_{K: \text{quadratic}} X_K \right) \cup X_{\mathbb{Q}}.$$

Let  $\mathcal{H}(G, \Gamma)$  be the Hecke algebra of  $G$  with respect to  $\Gamma$  and  $\mathcal{S}(\Gamma \backslash X)$  (resp.  $\mathcal{S}(\Gamma \backslash X_K)$ ,  $K =$  a quadratic field or  $\mathbb{Q}$ ) the space of finite  $\mathbb{C}$ -linear combinations of characteristic functions of  $\Gamma$ -orbits in  $X$  (resp.  $X_K$ ). The space  $\mathcal{S}(\Gamma \backslash X)$  becomes an  $\mathcal{H}(G, \Gamma)$ -module and

$$\mathcal{S}(\Gamma \backslash X) = \left( \bigoplus_{K: \text{quadratic}} \mathcal{S}(\Gamma \backslash X_K) \right) \oplus \mathcal{S}(\Gamma \backslash X_{\mathbb{Q}})$$

is a direct sum of sub  $\mathcal{H}(G, \Gamma)$ -modules. Our aim is to describe the  $\mathcal{H}(G, \Gamma)$ -module structure of  $\mathcal{S}(\Gamma \backslash X)$  explicitly. It is obvious that we need to consider the sub  $\mathcal{H}(G, \Gamma)$ -modules  $\mathcal{S}(\Gamma \backslash X_K)$  ( $K =$  a quadratic field or  $\mathbb{Q}$ ). We can see that each  $\mathcal{S}(\Gamma \backslash X_K)$  is a free  $\mathcal{H}(G, \Gamma)$ -module of

infinite rank. To see this, we introduce a kind of integral transform, which we call the *Fourier Eisenstein transform*, defined by taking the zeta functions of binary quadratic forms as a kernel function. Here the zeta functions of binary quadratic forms play a similar role to that of zonal spherical functions in the theory of the Satake transform of  $p$ -adic groups ([S1], [M1]).

In this note we consider only the case  $K = \mathbb{Q}$  and at the end of the note we shall give a brief indication how the result should be modified in the case of quadratic fields as well as a discussion on a possible generalization to higher dimensional symmetric spaces.

Finally we note that an analogous problem has been investigated by Y. Hironaka in [H] for the space of nondegenerate symmetric matrices over a  $p$ -adic number field.

## § 1. Fourier Eisenstein transform

1.1. For an  $x \in X_{\mathbb{Q}}$  we denote by  $x[u] = {}^t_{uxu}$  ( $u \in \mathbb{Q}^2$ ) the binary quadratic form corresponding to the matrix  $x$ . Put

$$Z_{\varepsilon, s}(x) = \sum_{\substack{u \in \mathbb{Z}^2 \\ x[u] \neq 0}} \text{sgn}(x[u])^{\varepsilon} |x[u]|^{-s_1} |\det x|^{-s_2}$$

( $s = (s_1, s_2) \in \mathbb{C}^2$ ,  $\varepsilon = 0, 1$ ) and

$$E_{\lambda}(x) = E_{\lambda_1, \lambda_2}(x) = \pi^{-s_1} \Gamma(s_1) \begin{pmatrix} \cos(\pi s_1/2) Z_{0, s}(x) \\ \sin(\pi s_1/2) Z_{1, s}(x) \end{pmatrix},$$

where  $\lambda = (\lambda_1, \lambda_2)$  is a variable which relates with  $s$

by

$$\begin{cases} s_1 = \lambda_2 - \lambda_1 + 1/2 \\ s_2 = \lambda_1 - \lambda_2 + 1/2. \end{cases}$$

Fundamental properties of the zeta function  $Z_{\varepsilon, s}(x)$  can be summarized as follows:

Proposition 1. (i)  $Z_{\varepsilon, s}(x)$  is absolutely convergent for  $\operatorname{Re} s_1 > 1$ .

(ii)  $Z_{\varepsilon, s}(x)$  has an analytic continuation to a meromorphic function of  $s$  in  $\mathbb{C}^2$ .

(iii) The following functional equation holds for any  $x \in X_{\mathbb{Q}}$ :

$$\Xi_{\lambda_2, \lambda_1}(x) = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \cdot \Xi_{\lambda_1, \lambda_2}(x).$$

1.2. Let  $\mathcal{H}(G, \Gamma)$  be the Hecke algebra of  $G$  with respect to  $\Gamma$ . The underlying vector space of  $\mathcal{H}(G, \Gamma)$  is by definition the space of all finite  $\mathbb{C}$ -linear combinations of characteristic functions of double cosets in  $\Gamma \backslash G / \Gamma$ . Denote by  $[g]$  ( $g \in G$ ) the characteristic function of the double coset  $\Gamma g \Gamma$ . The multiplication of  $[g_1]$  and  $[g_2]$  in  $\mathcal{H}(G, \Gamma)$  is defined as follows: Decompose the double coset  $\Gamma g_i \Gamma$  into left cosets

$$\Gamma g_i \Gamma = \bigcup_{j=1}^{k_i} g_{ij} \Gamma \quad (i = 1, 2)$$

and put

$$m(g_1, g_2; h) = \#\{(j_1, j_2); g_1 j_1 g_2 j_2 \Gamma = h \Gamma\} \quad (h \in G).$$

Then

$$[g_1] \cdot [g_2] = \sum_{\Gamma h \Gamma \in \Gamma \backslash G / \Gamma} m(g_1, g_2; h) [h].$$

Let  $C^\infty(\Gamma \backslash X_Q)$  be the space of all  $\Gamma$ -invariant  $\mathbb{C}$ -valued functions on  $X_Q$  and  $\mathcal{G}(\Gamma \backslash X_Q)$  its subspace of functions which vanish outside some finite union of  $\Gamma$ -orbits in  $X_Q$ . For  $\Phi \in C^\infty(\Gamma \backslash X_Q)$  and  $g \in G$ , we define the action of  $[g]$  on  $\Phi$  by

$$([g] * \Phi)(x) = \sum_{i=1}^k \Phi(g_i^{-1} x^t g_i^{-1}),$$

where  $\Gamma g \Gamma = \bigcup_{i=1}^k g_i \Gamma$  (disjoint union). Then it is easy to see that  $C^\infty(\Gamma \backslash X_Q)$  becomes an  $\mathcal{K}(G, \Gamma)$ -module and  $\mathcal{G}(\Gamma \backslash X_Q)$  is its  $\mathcal{K}(G, \Gamma)$ -submodule.

1.3. Since  $Z_{\varepsilon, s}(^t \gamma x \gamma) = Z_{\varepsilon, s}(x)$  for any  $\gamma \in \Gamma$ , we may regard  $Z_{\varepsilon, s}(x)$  as a function in  $C^\infty(\Gamma \backslash X_Q)$ .

**Proposition 2.** *There exists a  $\mathbb{C}$ -algebra homomorphism  $\omega_\lambda$  of  $\mathcal{K}(G, \Gamma)$  into  $\mathbb{C}$  satisfying*

$$(f * Z_{\varepsilon, s})(x) = \omega_\lambda(f) \cdot Z_{\varepsilon, s}(x)$$

for all  $f \in \mathcal{K}(G, \Gamma)$ . For any prime number  $p$ ,

$$\omega_\lambda\left(\begin{bmatrix} 1 & 0 \\ 0 & p \end{bmatrix}\right) = p^2(p^{-2\lambda_1} + p^{-2\lambda_2})$$

and for any non-zero rational number  $a$ ,

$$\omega_\lambda\left(\begin{bmatrix} a & 0 \\ 0 & a \end{bmatrix}\right) = |a|^{3-2(\lambda_1+\lambda_2)}.$$

Denote by  $\mathfrak{R}$  the restricted tensor product  $\bigotimes_p \mathbb{C}[p^{-2\lambda_1} + p^{-2\lambda_2}, p^{\pm 2(\lambda_1+\lambda_2)}]$ , where  $p$  runs through

all rational primes. Then it is known that  $\omega_\lambda$  gives rise to an algebra isomorphism of  $\mathcal{H}(G, \Gamma)$  onto  $\mathcal{R}$ .

For an  $x \in X_Q$  let  $ch_x \in \mathcal{G}(\Gamma \backslash X_Q)$  be the characteristic function of  $\Gamma$ -orbit containing  $x$ .

Definition. For a  $\Phi = \sum_i c_i ch_{x_i} \in \mathcal{G}(\Gamma \backslash X_Q)$

( $x_i \in X_Q$ ) we call

$$F_\varepsilon(\Phi)(\lambda) = \sum_i c_i Z_{\varepsilon, s}(x_i) \quad (\varepsilon = 0, 1)$$

the *Fourier Eisenstein transform* of  $\Phi$ .

Proposition 3.

- (i)  $F_\varepsilon(f * \Phi) = \omega_\lambda(f) \cdot F_\varepsilon(\Phi) \quad (f \in \mathcal{H}(G, \Gamma), \Phi \in \mathcal{G}(\Gamma \backslash X_Q)).$
- (ii)  $F_\varepsilon(\Phi_1) = F_\varepsilon(\Phi_2) \quad \text{if and only if} \quad \Phi_1 = \Phi_2$   
 $(\Phi_1, \Phi_2 \in \mathcal{G}(\Gamma \backslash X_Q)).$

1.4. For positive rational numbers  $r$  and  $q$ , we denote by  $ch_{q, r}$  the characteristic function of the  $\Gamma$ -orbit containing  $r \cdot \begin{pmatrix} q & 1 \\ 1 & 0 \end{pmatrix}$ . Let  $N$  be a positive integer. We define an equivalence relation on  $(\mathbb{Z}/(N))^{\times}$  as follows:

$$x \sim y \iff x = y \text{ or } y^{-1} \quad (x, y \in (\mathbb{Z}/(N))^{\times}).$$

Then the set

$$\left\{ ch_{m/N, r}; \begin{array}{l} r \in \mathbb{Q}, r > 0, N \in \mathbb{Z}, N \geq 1 \\ m = 0, \text{ if } N = 1, \\ m \in (\mathbb{Z}/(N))^{\times}/\sim, \text{ if } N \geq 2 \end{array} \right\}$$

forms a  $\mathbb{C}$ -basis of  $\mathcal{G}(\Gamma \backslash X_Q)$ .

For a primitive Dirichlet character  $\chi$  with conductor  $f_\chi$ , we define a linear mapping

$$T_\chi: \mathcal{G}(\Gamma \backslash X_Q) \longrightarrow \mathcal{G}(\Gamma \backslash X_Q)$$

by

$$T_\chi(ch_{m/N, r}) = \varphi(f_\chi N)^{-1} \sum_{\alpha \in (\mathbb{Z}/(f_\chi N))^{\times}} \chi(\alpha) ch_{\alpha m/N, r},$$

where  $\varphi(\ )$  stands for the Euler function.

Proposition 4.

- (i)  $T_\chi(ch_{m/N, r}) = 0$  unless  $f_\chi$  divides  $N$ .
- (ii)  $T_\chi = T_{\bar{\chi}}$  and  $T_\chi \circ T_\chi = T_\chi$ .
- (iii) For any primitive Dirichlet characters  $\chi$  and  $\psi$   $T_\chi \circ T_\psi = T_\psi \circ T_\chi = 0$  unless  $\chi = \psi$  or  $\bar{\psi}$ .
- (iv)  $T_\chi$  commutes with the action of  $\#(G, \Gamma)$  on  $\mathcal{G}(\Gamma \backslash X_Q)$ .

For a square free positive integer  $m$ , we put

$$\mathcal{G}(\Gamma \backslash X_Q)_{\chi, m} = \#(G, \Gamma) \cdot T_\chi(ch_{1/f_\chi, m}).$$

It is obvious that  $\mathcal{G}(\Gamma \backslash X_Q)_{\chi, m} = \mathcal{G}(\Gamma \backslash X_Q)_{\bar{\chi}, m}$ .

Theorem. (i) For a primitive Dirichlet character  $\chi$ , set  $\varepsilon_\chi = 0$  or  $1$  according as  $\chi(-1) = 1$  or  $-1$ .

For  $\Phi \in \mathcal{G}(\Gamma \backslash X_Q)_{\chi, m}$ , set

$$F_{\chi, m}(\Phi) = F_{\varepsilon_\chi}(\Phi) \cdot 2^{s_1-2} f_\chi^{-s_1} m^{\lambda_1+\lambda_2} \varphi(f_\chi) / L(s_1, \chi) L(s_1, \bar{\chi}),$$

where  $L(s, \chi)$  is the Dirichlet  $L$ -function. Then  $F_{\chi, m}(\Phi)$  is in  $\mathbb{R}$  and the mapping

$$F_{\chi, m}: \mathcal{G}(\Gamma \backslash X_Q)_{\chi, m} \longrightarrow \mathbb{R}$$

is a linear isomorphism and the following diagram is commutative:

$$\begin{array}{ccc}
 \mathcal{H}(G, \Gamma) \times \mathcal{G}(\Gamma \backslash X_Q)_{\chi, m} & \xrightarrow{*} & \mathcal{G}(\Gamma \backslash X_Q)_{\chi, m} \\
 \omega_\lambda \times F_{\chi, m} \downarrow \simeq & & F_{\chi, m} \downarrow \simeq \\
 \mathcal{R} \times \mathcal{R} & \xrightarrow{\text{multiplication}} & \mathcal{R}
 \end{array}$$

In particular  $\mathcal{G}(\Gamma \backslash X_Q)_{\chi, m}$  is a free  $\mathcal{H}(G, \Gamma)$ -module of rank 1.

(ii) Let  $\mathfrak{I}$  be the set of all Dirichlet characters.

Then as  $\mathcal{H}(G, \Gamma)$ -modules, we have the decomposition

$$\mathcal{G}(\Gamma \backslash X_Q) = \bigoplus_{\chi \in \mathfrak{I} / \sim} \bigoplus_{m: \text{square free}} \mathcal{G}(\Gamma \backslash X_Q)_{\chi, m},$$

where the equivalence relation  $\sim$  on  $\mathfrak{I}$  is defined by

$$\chi \sim \psi \iff \chi = \psi \text{ or } \bar{\psi}.$$

Thus  $\mathcal{G}(\Gamma \backslash X_Q)$  is a free  $\mathcal{H}(G, \Gamma)$ -module of infinite rank.

Remark. For a  $\Phi \in \mathcal{G}(\Gamma \backslash X_Q)_{\chi, m}$ , we have  $F_\varepsilon(\Phi) = 0$ , if  $\varepsilon \neq \varepsilon_\chi$ .

The proof is based on the following explicit calculation of the Fourier Eisenstein transform, namely the zeta functions of binary quadratic forms.

Proposition 5. For a positive rational number  $r$ , a positive integer  $N$  and an integer  $m$  with  $(N, m) = 1$ , we have

$$\begin{aligned}
 F_\varepsilon(ch_{m/N, r})(\lambda) &= 2^{2-s_1} r^{-s_1-2s_2} N^{-s_1} \\
 &\times \sum_{M|N} \varphi(m)^{-1} M^{2s_1} \sum_{\substack{\chi \bmod M \\ \chi(-1)=(-1)^\varepsilon}} \chi(m) L(s_1, \chi) L(s_1, \bar{\chi}).
 \end{aligned}$$



## § 2. Remarks

2.1. For a quadratic field  $K$ , we can define a Fourier Eisenstein transform of  $\mathcal{G}(\Gamma \backslash X_K)$  by using zeta functions of binary quadratic forms (irreducible over  $\mathbb{Q}$ ). An analogue of the intertwining operator  $T_\chi$  is obtained from characters of the class groups of orders of  $K$  and we can get a structure theorem of  $\mathcal{G}(\Gamma \backslash X_K)$  quite similar to the theorem above.

If  $K$  is an imaginary quadratic field, Mautner [M2] obtained essentially the same result, though he employed the formulation in terms of  $PGL(2)$  rather than  $GL(2)$ . However, since he reduced the things to the local case, the role played by the zeta functions of binary quadratic forms is not clear in his work.

2.2. It is likely that the result of this paper can be generalized to higher dimensional (not necessarily Riemannian) reductive symmetric spaces defined over  $\mathbb{Q}$ . In a general case a kernel function of the Fourier Eisenstein transform will be Eisenstein series of the type introduced in [S3] (see also [S2], [S4]). In particular, if Eisenstein series has an Euler product expansion, then the theory of the Fourier Eisenstein transform will be a synthesis of local theories (theory of spherical functions on symmetric spaces over  $p$ -adic number fields). Such examples are supplied by

$$(i) \quad G = GL(2n), \quad X = GL(2n)/Sp(n)$$

= the space of nondegenerate  
alternating forms.

$$(ii) \quad G = G_0 \times G_0, \quad X = G_0 \times G_0 / \Delta(G_0) \simeq G_0,$$

where  $G_0$  is a simply connected Chevalley group over  $\mathbb{Q}$ .

The corresponding local theory is given by [HS] for the first example and by the theory of zonal spherical functions on  $p$ -adic reductive groups ([S1], [M1]) for the second example.

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